Fabricate and Assemble: An Alignment and Integration Method for Next Generation X-ray Telescopes

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ABSTRACT

Future X-ray telescopes invariably require much higher angular resolutions and/or much larger effective areas than those already flown, and they will typically be designed and built with mirror segments, in contrast with the typical past X-ray telescope of complete shells. While the segmented approach has many advantages, it has one significant disadvantage: its complexity and difficulty associated with mirror segment alignment and integration. In this paper, we outline an approach, named "Fabricate and Assemble," that directly addresses this disadvantage. We will describe the necessary components, their fabrication, and their integration into a mirror assembly. The salient features of this approach include: (1) it fully realizes the optical performance potential of each mirror segment, (2) it leaves each mirror in a stress-free or minimally stressed state, resulting in a stress-free and therefore stable mirror assembly, (3) it assembles the mirror segment while it is supported so as to minimize or even eliminate the effect of gravity, and (4) it is highly amenable to being implemented as part of a sequential production line.

Keywords: X-ray optics, lightweight optics, Constellation-X, space optics

1. INTRODUCTION

Future large X-ray telescopes will most likely be made of many mirror segments, in direct contrast with existing ones, like Chandra and XMM/Newton, which were made of integral shells. The advantages of the segment approach are manifold. It is highly amenable to the mass production of mirror segments, resulting in significant reduction of mirror fabrication cost. It does not require the build-up of larger equipment and facilities, such as coating chambers, grinding and polishing machines, and metrology equipment, than those already existing in industry and in government or university laboratories. It does, however, have a significant disadvantage, i.e., for a given telescope assembly, it has significantly more mirror elements to align and integrate. This represents a significant challenge, given the integration precision required and very small space between mirror segments.

This challenge can be met straightforwardly. Having studied and drawn lessons from past and existing techniques, including those of BBXRT, ASCA, Suzaku (Serlemitsos 1988), HEFT (Craig et al. 1998), and several techniques that have been studied for the Constellation-X mission (Bergner et al. 2000, Hair et al. 2003, and Owens et al. 2006), we propose a new technique that we call "Fabricate and Assemble." As the name suggests, every component is separately fabricated and verified with metrology before they are brought together for integration.

2. THE FABRICATE AND ASSEMBLE METHOD and ITS KEY COMPONENTS

The entire method is illustrated in Figure 1. Key components of the process are identified and briefly described in Table 1. The glass forming technique, which is central to the Fabricate and Assemble method, is described elsewhere (Zhang et al. 2006). Suffice it to say that the alignment spacers are fabricated the same way as the mirror segments themselves: formed on the same mandrel to ensure the surface curvature to be precisely the same as that of the mirror segment. Once a mirror segment is fabricated and coated, it is measured and qualified to meet its own requirements using interferometers and coordinate measuring machines. An essential aspect of this metrology process is to adequately support the mirror segment without distortion (or with tolerable minimal) distortion caused by gravity and friction.

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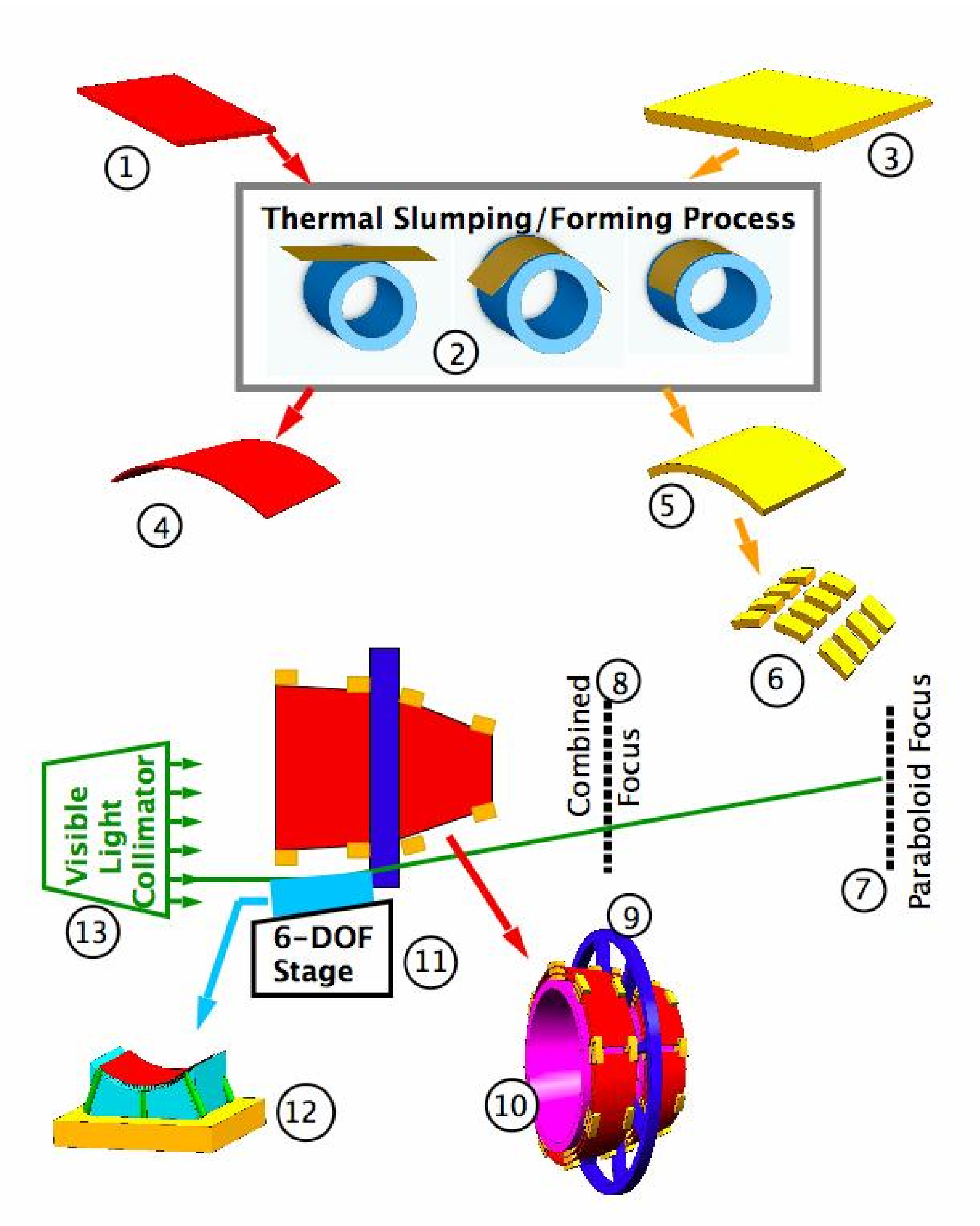

Figure 1. A pictorial illustration of the Fabricate and Assemble method. See Table 1 for the identification and a brief description of each of these items.

Table 1. Identification and brief descriptions of the items in Figure 1. Key components are highlighted in red and are discussed in the text.

Item ID	Description	Comment
1	Commercially available glass sheet: Schott D263, a typical borosilicate glass, available thicknesses ranging from 0.03mm to 1.1mm	No technical development needed
2	Glass slumping/forming process	Essential part of this method, see Zhang et al. (2006)
3	Wedged glass sheet; Specifically designed and fabricated (lapped) to meet well-defined, but relatively loose tolerance	These wedges can be obtained commercially and inexpensively
4	Finished mirror segment, after slumping and trimming	Trimming process has been developed.
5	Wedged sheet after slumping/forming	Part of the slumping process
6	The wedged sheet has been cut into small rectangles to be used as alignment spacers	Cutting the slumped wedge into many small pieces can be done with a diamond saw.
7	Focal plane of the parabolic mirror segment	Engineered with an optical CCD
8	Focal plane of the parabolic-hyperbolic two-reflection system	Engineered with an optical CCD
9	Mirror assembly mounting flange or wagon-wheel to which every mirror segment is attached on the spokes	Very loose tolerances; Easily done with regular machining,
10	Alignment cores (parabolic and hyperbolic); Precision diamond-turned	Not challenging; Several commercial vendors are capable and willing to machine them.
11	Six degrees of freedom (6-DOF) stage for positioning the mirror segment	Easily procured commercially
12	Specially designed and fabricated mattress for supporting the flimsy mirror segment with minimal distortion	Mildly challenging; Will be done in-house.
13	Light collimator for generating a parallel beam to monitor the alignment process	Commercially available equipment

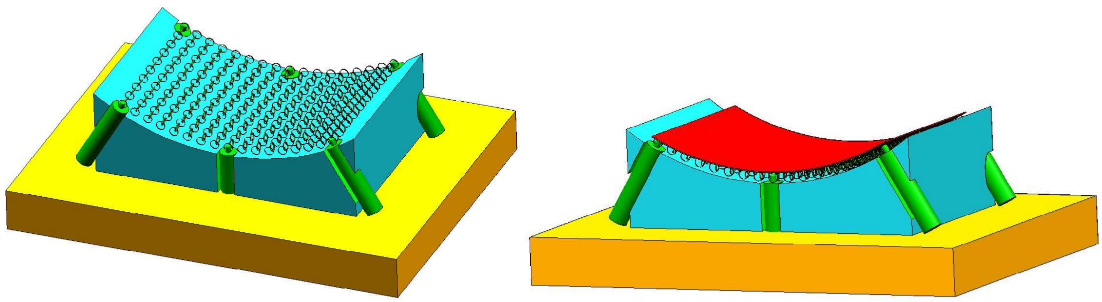

Figure 2. Illustrations of the mirror mattress. The mirror is supported at hundreds of points by very soft "springs" to reduce, or even eliminate, gravity distortion. The green tubes are piston-like actuators that will push the mirror against integration spacers once the mirror has been determined to be in the right configuration.

2. 1 Mirror Mattress

Essential to both the post-fabrication metrology process and the later integration process is the mirror mattress, as shown in Figure 2. It consists of two parts. The solid part (light blue in Figure 2) is milled out of a piece of metal, aluminum or titanium. It has a conical shape with typical machining precision, ~25 μm. On the concave surface is laid a large number, several hundred to several thousand, very soft "springs," as shown in the left panel in Figure 2. These little springs could be made of small loops of Mylar strips, which are extremely resilient and elastic.

The operating principle of the mattress is straightforward. The weight of the mirror is borne and shared by the many springs. Because the springs are much more flexible and softer than the mirror, when adjustment is needed to balance the weight due to either a spring having a wrong height or a wrong spring constant, it is the spring that gives, not the mirror. The following condition is necessary and sufficient: the amount of compression a spring sustains under its share of the mirror weight has to be *much larger* (~10^3 times) than the combined magnitude of irregularity of the solid cradle surface and irregularity on the back of the mirror. In practice, this condition is easily met by using very thin Mylar strips. A preliminary analysis (similar to that reported in Nelson, Jacob, & Mast 1982) and experiment has shown that with 400 springs supporting a typical mirror segment (200mm by 220mm by 0.4mm with a mass of 45 grams), a figure deformation of much less than 1″ is expected. This number can be made even smaller by using more and softer springs.

2.2 Alignment and Integration Spacers

Each spacer (shown as small yellow rectangles in Figure 1) is characterized by three parameters: (1) thickness taper in the optical axis direction, (2) radial thickness, and (3) curvature.

The thickness taper and radial thickness are achieved by starting with a wedged glass sheet that is specially fabricated for making alignment spacers. It is lapped to have a shell-specific slope or taper in thickness. Its center thickness is approximately the average space between two adjacent shells. In principle, this wedge should be made of the same glass as the mirror sheet. But in practice, it only needs to match the coefficient of thermal expansion (CTE) of the mirror sheet.

The wedged sheet, for example, measuring 90×60 mm^2, is slumped on the same mandrel as the mirror segment to ensure it has the same curvature. The slumped wedge is cut/diced into many small (approximately 3×3 mm^2) spacers, resulting in many (~600) spacers covering a radial thickness span of 10's of microns. Each of these spacers will have its thickness measured and documented to 0.1 µm. A Mitutoyo LSM-902/6900 or equivalent laser thickness gauge will be used for this purpose. It is capable of measuring thickness to an accuracy of 0.05µm.

In principle, a fairly small number (~100 per shell) of spacers with well-defined radial thicknesses are needed. But these thicknesses are not known a priori because they depend on the thickness variation of the mirror on which they will be attached. The large number of spacers of various thicknesses ensures that there be plenty of them from which to select the ones with the precisely needed thicknesses. More importantly, it is much easier to fabricate a wedged sheet than to fabricate a few isolated spacers.

2.3 Alignment Cores

The alignment cores consist of three parts: the wagon wheel, the parabolic (primary) core, and the hyperbolic (secondary) core. The wagon wheel, made of titanium (or even glass of the same type as the mirror segment) to match the coefficient of thermal expansion of the glass mirrors, does not have to be precision machined. It is a central mechanical structure to which each mirror segment is attached. Eventually it serves as the interface (mounting flange) to the optical bench.

The parabolic and hyperbolic cores are the starting point of the mirror integration process. Since they will be removed at the completion of the integration, they can be made sufficiently thick and stiff. In principle, they do not have to be precision machined. But because of their axial symmetry nature, they can be turned extremely accurately on a commercially available diamond turning machine. They are made of titanium plated with nickel to facilitate diamond turning. The two cores can be a single integral piece or can be two separate pieces aligned and bonded together. We will determine which of these two options to adopt in consultation with diamond turning experts available in a number of institutions and companies, including NASA Marshall Space Flight Center and Corning NetOptix, Inc., located in Keene, New Hampshire.

2.4 Mirror Alignment and Integration Process

The alignment and integration process is depicted in the lower part of Figure 1. Several features of this system should be noted. First, the optical axis is defined by the parallel beam out of the collimator. Second, the alignment core as defined by the parabolic and hyperbolic parts is attached to a precision (air-bearing) rotation stage, not shown in Figure 1. The rotational axis of the core, which, by definition, is also the optical axis of the mirror assembly, must be co-aligned with the parallel beam. Third, there is a radius gauge, not shown in Figure 1, that is capable of measuring the relative radius to an accuracy of 0.1 µm, with relative radius meaning the radii at three of the four positions, parabolic forward (X-ray entrance to the mirror assembly), parabolic aft, hyperbolic forward, and hyperbolic aft (X-ray exit from the mirror assembly), with respect to the radius of the fourth.

Once the core is aligned with the parallel beam, the first task is to install the spacers at appropriate positions for the first parabolic mirror segment. The radius gauge measures the exact radial height at each position, based on which, an appropriate spacer is selected and attached with adhesive. After the spacers have been firmly in place, i.e., after they are properly bonded and adhesive cured, an appropriate amount of epoxy is applied to the outer surface of each spacer. Then the first parabolic mirror segment is moved into place using the mirror segment mattress and the 6-DOF stage. The entire movement process is monitored by the optical image on the parabolic focal plane. In practice both images in the focal plane and slightly out-of-focal-plane rings are also monitored. The diffraction limit of the visible light is overcoming by using the centroiding capability of the CCD. There is built-in redundancy to verify the configuration of the mirror segment: the parallel beam of light forming image on the focal plane, and the mirrors coming into contact with the spacers/epoxy. Once the mirror segment is in its right place, an appropriate amount of pressure is applied on the mirror at the position of each of the spacers by the "pistons," shown in green in Figure 7. The epoxy cures while these pressures and the mattress supporting the mirror segment are continuously maintained.

Once the first parabolic mirror segment is firmly attached, the next mirror is its radially adjacent parabolic mirror segment. Then it will be the hyperbolic mirror segment corresponding to the first parabolic mirror. In other words, the sequence is Parabolic, Parabolic, Hyperbolic, Parabolic, Hyperbolic…. for a particular azimuth sector.

3. CONLUSIONS

We have outlined the Fabricate and Assemble approach. Its salient features are: (1) it does not distort, as such it makes the best use of, each mirror segment; (2) it integrates each mirror segment into the assembly stress-free, preventing the finished mirror assembly from possible distortion caused by stress built up from the large number of mirror segments; (3) it integrates each mirror segment into the assembly with its "gravity-free" figure such that the mirror assembly will achieve its best performance once launched into space; and (4) it is easily implemented as part of a sequential production line.

Key components that need to be proved include the mirror mattress, the fabrication of the spacers, and the application of adhesive at the position of each of the spacers. In principle, the limit of the mirror mattress's ability to hold the mirror segment free of figure distortion is the ultimate integration precision of this method.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

1. Craig, W. et al, 1998, SPIE Proc. Vol. 3445, p. 112
2. Hair, J. et al. 2003, SPIE Proc., Vol. 4851, p. 696
3. Nelson, J.E., Jacob, L., and Mast, T.S., 1982, Proc. SPIE, Vol. 332 p. 212
4. Owens, S. et al, 2006, in these proceedings
5. Serlemistsos, P.J., 1988, Appl. Opt. Vol. 27, p. 2447
6. Zhang, W.W. et al., 2006, in these proceedings